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# TECHNICAL NOTE

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# THERMAL-STRESS FATIGUE CRACKING OF TURBINE BUCKETS OPERATED AT 1700° F IN A TURBOJET ENGINE WITH FREQUENT STARTS AND STOPS

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# THERMAL-STRESS FATIGUE CRACKING OF TURBINE BUCKETS OPERATED AT 1700° F IN A TURBOJET ENGINE WITH FREQUENT STARTS AND STOPS

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## SUMMARY

Five high-strength nickel-base bucket materials were tested in a J47 turbojet engine at 1700° F. The investigation was conducted to study the effects of advanced-temperature operation on thermal-stress fatigue resistance of several of the newer turbine-bucket alloys. Inadvertently, the buckets were subjected to frequent starts and stops during the test. The bucket materials used in the test were SEL-1, B and B, Inconel 713, cast Udimet 500, and wrought Udimet 500.

Thermal-stress fatigue cracking on the leading edge of the buckets was observed in all alloy groups after short operating times. Cracks occurred in some groups after only 10 starts ($6\frac{1}{2}$ hr at rated speed) and had occurred in all groups after 28 starts (30 hr). At the conclusion of the test (49 starts and 70 hr), 60 to 90 percent of the buckets of each alloy had developed cracks. Thermal-stress fatigue cracks did not progress rapidly by stress-rupture to cause fracture of buckets. Only one bucket fractured during the test; a thermal-stress fatigue crack progressed by mechanical fatigue to fracture. This bucket was run with cracks for 31 hours before fracture. Other buckets ran with cracks for as long as 63 hours without fracture.

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## INTRODUCTION

The need for turbine-bucket materials for use at continually higher turbine-bucket temperatures has led to the development of alloys with improved properties at these temperatures. The alloys in this study, SEL-1, B and B, Inconel 713, cast Udimet 500, and wrought Udimet 500, are examples of some newer nickel-base alloys. These alloys have stress-rupture properties that indicate turbojet bucket "use temperatures" as high as 1800° F, with a possible life of 100 hours or more.

However, the complex combination of variables contributing to failure of buckets during engine operation prevents an accurate prediction of either the bucket life or the mode of failure based on laboratory test data alone. The relative importance of different modes of failure varies with the engines. For example, in one engine of high centrifugal bucket stress (J33) the modes of failure were found to be primarily stress-rupture and mechanical fatigue (refs. 1 and 2). In the J47 engine, with a relatively low centrifugal bucket stress, the primary mode of bucket failure was shown to be thermal-stress fatigue cracking at the leading edge (refs. 3 to 5). These studies conducted at 1500° F bucket temperatures included standard alloys such as M-252 and S-816. It should be noted that thermal-stress fatigue cracking also occurs in other engines as well as the J47 and is considered a serious problem.

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It was believed that rated-speed operation at 1700° F might have a more pronounced effect on initiating thermal-stress fatigue cracks in the alloys considered for this study than did operation at 1500° F with M-252 and S-816 in earlier studies (refs. 3 and 4). The reason for believing that crack initiation would be affected may be seen from the following discussion. A study of the various phases of J47 engine operation has indicated that thermal stresses generated in buckets during starting are the primary cause of leading-edge cracking (ref. 5). Since the starting conditions are no different for 1700° F operation than for 1500° F, it might be argued that no effect could be expected. However, reference 5 also showed that even a small amount of operation at full-power conditions (i.e., rated-speed conditions where buckets attained a temperature of 1500° F) reduced the number of starts required to initiate cracking. Reductions by factors of 2 and 4, respectively, for M-252 and S-816 were obtained when each start was followed by 15 minutes of rated-speed operation at 1500° F. Certainly if rated-speed operation at 1700° F is a more severe condition for the newer alloys than was operation at 1500° F for M-252 and S-816, an adverse effect on crack initiation might be expected with the newer alloys.

The relative severity of rated-speed conditions at 1500° and 1700° F for all the alloys under discussion is shown by a comparison of the predicted stress-rupture lives of buckets of all of these alloys. If centrifugal stress and temperature were assumed to be the only factors contributing to bucket failure, the predicted life of S-816 and M-252 buckets in a J47 engine at rated speed and 1500° F would be at least 10,000 hours, whereas the predicted lives of the alloys considered herein at rated speed and 1700° F would extend only from 800 to 3000 hours (see ref. 4 for methods of predicting life). Thus, the greatly increased severity of rated-speed operation at 1700° F with the newer alloys is apparent.

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It was believed that the rate and mode of propagation of cracks to complete fracture might also be affected. In the earlier investigations (refs. 3 and 4), buckets with leading-edge cracks (M-252, S-816, and other materials) ran at rated speed and 1500° F for several hundred hours after initiation of leading-edge cracks. In these instances fracture finally occurred by progression of a crack initiated by thermal-stress fatigue but propagated through a mechanical fatigue process. Because of the lower predicted lives at 1700° F of the newer alloys considered in this investigation, a leading-edge crack, once initiated, might conceivably progress very rapidly. Also, it might be expected that crack propagation would occur by a stress-rupture mechanism rather than mechanical fatigue.

This investigation was therefore conducted to study the effect of engine operation at 1700° F on the resistance to thermal-stress fatigue cracking of turbojet-engine buckets of some of the newer nickel-base alloys and to study the mode and rate of propagation of the cracks. Buckets of alloys SEL-1, B and B, Inconel 713, cast Udimet 500, and wrought Udimet 500 were operated at 1700° F in a J47 engine. The engine was operated using the normal operating cycle, 15 minutes of rated speed and 5 minutes at idle speed. Because of mechanical difficulties occasioned by the high test temperature, the engine was frequently shut down for necessary repairs. This caused a high frequency of starts compared with similar tests run previously at 1500° F. However, the frequency of starts was no greater than that which a military fighter-engine installation might experience.

## MATERIALS, APPARATUS, AND PROCEDURE

### Bucket Materials

Investment-cast buckets of alloys SEL-1, B and B, Inconel 713, and Udimet 500, and wrought buckets of Udimet 500 were obtained from commercial sources and evaluated in this engine test. The chemical composition of each alloy is shown in table I. The Inconel 713 buckets were received in the as-cast condition, while all other bucket groups were in the as-heat-treated condition. The number of buckets of each alloy engine-tested and the heat treatment applied to each alloy group are shown in table II. All buckets were inspected before engine testing, using X-ray radiography and fluorescent dye penetrant methods. Buckets were required to be free of defects detectable by X-ray radiography and were allowed to contain only a limited number of small surface defects in the central portion of the airfoil and in the base.

## Engine Modification for 1700° F Operation

Other than the turbine buckets, the most critical components in the hot section of a J47 engine are the turbine stator blades and the turbine disk. These components normally operate very close to the design limits of the materials at rated-speed and rated-gas-temperature conditions. For this reason, it would be necessary to substitute components made of other more heat-resistant materials or to provide cooling in order to test the buckets above normal operating temperatures. In this investigation it was more practical, as well as more economical, to cool these components rather than fabricate them from other materials. Cooling systems were designed to maintain normal operating temperatures in each of these components when the engine was operated at the elevated test temperature (buckets at 1700° F).



Modifications to provide cooling of turbine stator blades are illustrated in figure 1. These blades, which are normally uncooled, were cooled by air from an auxiliary source. The air was passed into a manifold welded to the inner spacer band, through the hollow blades, through holes in the outer spacer band, and into the gas stream ahead of the turbine buckets. Corrugated inserts guided the air along the inner surfaces of the stator blades for more efficient cooling. The turbine disk in a standard J47 engine is normally cooled by air bled from the compressor and directed to both upstream and downstream faces. Normally air is provided at a rate of 1/2 pound per second to cool each disk face. An additional $1\frac{1}{2}$ pounds per second of air was bled from the compressor to supply the added cooling needed to maintain normal operating temperatures in the disk. The additional cooling air was supplied to the downstream face by merely increasing the size of the air line. Cooling of the rim area of the upstream face of the disk was provided by bleed air ducted through an annular nozzle positioned near the upstream face.

In addition to the installation of auxiliary cooling systems, it was necessary to increase fuel flow to run with a bucket temperature of 1700° F. The operation of the engine fuel-flow regulator was altered to obtain the necessary high fuel flow. The engine fuel regulator normally meters fuel in accordance with the discharge pressure of the compressor. It was possible to alter the fuel flow during rated-speed operation merely by supplying air pressure from an auxiliary source to the regulator sensing element. This high-pressure air caused the regulator to supply fuel at a higher rate, as it would normally do if the engine were operated at high-ram-pressure conditions. To permit normal operation during starting and accelerating from idle to rated speed, the auxiliary air supply was shut off during these operations and only compressor discharge air was supplied to the regulator sensing element.

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## Stress and Temperature Distribution in Buckets

Centrifugal stress and temperature distribution in bucket airfoils at rated-speed and advanced-temperature conditions are shown in figure 2. The centrifugal stress was calculated by the method of reference 6, using the bucket geometry, material density, and engine rotational speed. The temperature distribution shown in figure 2 was obtained before the materials test was started. To do this, the engine was operated with standard S-816 alloy buckets for sufficient time to obtain equilibrium conditions at rated speed. Temperature measurements were obtained from thermocouples imbedded in four turbine buckets.

## Engine Operation

For the actual materials testing of this investigation, a turbine wheel containing 94 test buckets and two thermocoupled buckets was installed in a J47-25 engine. The engine was operated for repeated cycles of 15 minutes at rated speed (7950 rpm) and about 5 minutes at idle speed (3000 rpm). Engine operation was interrupted for maintenance, repairs, and at the end of each work day. Operation of the engine at advanced temperature caused frequent shutdowns for minor engine repairs; thus no intentional shutdowns were required for bucket inspection.

Bucket stress and temperature were controlled during the engine test at the previously measured conditions shown in figure 2 by adjusting the engine speed and exhaust-nozzle area, respectively. Bucket temperatures were monitored with a thermocouple imbedded at midspan in each of two S-816 alloy buckets. Since S-816 does not have sufficient rupture strength to operate for more than about 20 hours at $1700^{\circ}$ F in a J47 engine, a 5/8-inch section was cut from the tip of the airfoil to reduce centrifugal stresses to an acceptable level. Previous studies had indicated that shortening the buckets by this amount did not measurably change the temperature-distribution readings. Temperature readings were transmitted through slip-rings to a recording potentiometer in a manner similar to that described in reference 7.

## Bucket-Elongation Measurements

Two buckets of each alloy group were scribed for elongation measurements at 1/2-inch intervals (as shown in fig. 3). Elongation readings of scribed zones were taken at convenient time intervals and at the conclusion of the test. The measurements were made with an optical micrometer having a sensitivity of 0.0001 inch. However, because of the width of the scribe marks, bowing of bucket airfoils, and human error, elongation readings were actually significant to $\pm 0.001$ inch or $\pm 0.2$-percent elongation in each 1/2-inch-gage length.

### Macroexamination of Buckets

Buckets were examined for cracks using fluorescent-dye-penetrant inspection after intervals of about 5 hours of rated-speed operation. The number of buckets of each group with thermal-stress fatigue cracks was recorded at each inspection. Cracked buckets were considered failed but were reinserted in the engine for further test along with unfailed buckets to study the propagation of cracking to fracture.

### Metallographic Studies

Two untested buckets and two tested buckets from each alloy group listed in table II were sectioned for metallographic examination. An area near the leading edge at midspan was examined to determine the general microstructure in each alloy group.

## RESULTS AND DISCUSSION

### Bucket Failures

During the total time of the engine test (70 hr), only one bucket fractured. However, large numbers of buckets failed by thermal-stress fatigue cracking. Typical cracked buckets shown in figure 4 are similar to those observed in previous investigations (refs. 3 to 5) with a multiplicity of cracks over a considerable portion of the leading edge. Bucket failure data are presented in figure 5, plotted against starts and stops rather than against time, since this was the primary cause of thermal-fatigue cracking, as was cited earlier from reference 5. Hence, in figure 5, the position of each data point indicates the number of start-stop cycles at which cracks were first observed in each bucket. A time scale, although nonlinear, is shown also, for convenience. Cracking began after relatively few starts. Buckets of cast Udimet 500 and SEL-1 cracked after 10 starts ($6\frac{1}{2}$ hr at rated speed), Inconel 713 after 12 starts (10 hr), and B and B and forged Udimet 500 after 28 starts (30 hr). The number of buckets with cracks increased at a relatively rapid rate after the first bucket cracked. The numbers of starts to crack 50 percent of the buckets (i.e., the median life) of each alloy group as indicated by the arrows in figure 5 are as follows: 24 for cast Udimet 500, 28 for Inconel 713, 29 for SEL-1, 36 for forged Udimet, and 45 for B and B. The median life of the B and B alloy buckets, the most crack-resistant group, is almost double that for cast Udimet 500, the least crack-resistant group. However, by the end of the test, 70 hours at rated speed and 49 starts, 60 to 90 percent of the buckets in each alloy group were cracked, as may be seen in figure 5.

Thermal-stress cracking occurred more readily (with fewer starts) with the alloys tested in this investigation at 1700° F than with S-816 and M-252 buckets operated at 1500° F in previous engine tests. About 20 and 100 starts, respectively, were required to initiate cracking in M-252 and S-816 buckets operated at 1500° F (ref. 4). This compares with 10 to 28 starts for the alloy groups tested in this investigation at 1700° F. Thus, from the results of this investigation, it appears that operation of these newer alloys at 1700° F in a J47 engine poses a more serious thermal-fatigue cracking problem than has been experienced with standard bucket materials operated at normal rated-speed conditions.

As described in the INTRODUCTION, the relatively low predicted stress-rupture life of the alloys tested in the engine raised the possibility that cracked buckets might progress to fracture with short times at rated speed and by a stress-rupture mechanism rather than by mechanical fatigue. Actually, only one bucket fractured during the 70-hour test. This was an Inconel 713 bucket that fractured after 51 hours at rated speed. The bucket failed by mechanical fatigue progression of a thermal-fatigue crack. The mechanism was typical of fractures encountered in the prior investigations (refs. 3 and 4). The Inconel 713 bucket ran with thermal-fatigue cracks for 31 hours before fracture, and other buckets in the present investigation ran with similar cracks up to 63 hours without fracture. Thus, rapid progression of cracks by stress-rupture to fracture did not occur.

The mechanism of crack propagation experienced in this investigation may have been influenced by the number of starts encountered. It has been shown in previous engine tests (ref. 5) that thermal-stress fatigue cracks can be initiated in the buckets by a relatively small number of starts where little or no rated-speed operation is involved. During this investigation, the difficulties encountered with engine operation at higher than normal temperatures caused a great number of starts relative to a small amount of time accumulated at rated speed. Hence, in this test, cracks were initiated in the buckets before any appreciable portion of the stress-rupture lives of the alloys had been expended. This could explain why the thermal-fatigue cracks did not progress rapidly to fracture by a stress-rupture mechanism. If longer periods of engine operation between starts were possible, the inception of cracks would probably occur after a considerable portion of the stress-rupture life of the buckets had been expended. This in turn could make buckets more susceptible to rapid progression of the thermal-stress cracks to fracture by a stress-rupture mechanism. This possibility could be evaluated by an engine endurance test in which measures would be taken to reduce the frequency of starts.

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## Bucket Elongation

No measurable elongation of bucket airfoils (less than 0.2-percent elongation) was detected. It may be recalled that readings of elongation of two buckets of each alloy group were taken at convenient intervals and at the conclusion of the test. The fact that the bucket elongation was very low would seem to indicate that creep was in a very early stage. This might also be expected from the limited time at rated speed accumulated during the entire test.

## Metallography

Photomicrographs of general structures of buckets of all alloy groups are shown in figure 6. All the structures appear similar, with a fine precipitation of minor phases throughout the grains, as is typical of high-temperature nickel-base alloys. No noticeable change in microstructure for any of the alloy groups was apparent after 70 hours of engine operation. Consequently, only photomicrographs of untested buckets are shown.

# SUMMARY OF RESULTS

Buckets of alloys SEL-1, B and B, Inconel 713, cast Udimet 500, and wrought Udimet 500 were operated in a J47 engine with a bucket material temperature of 1700° F. The engine was operated for cycles of 15 minutes at rated speed and 5 minutes at idle speed. The buckets were subjected to frequent starts and stops during the test. The following results were obtained:

1. Thermal-stress fatigue cracking on the leading edge of buckets was the primary mode of failure. From 60 to 90 percent of the buckets of each alloy group had developed cracks when the engine test was discontinued after 70 hours and 49 starts.

2. Buckets failed by cracking with very few starts and short operating times. Buckets of alloys Udimet 500 (cast), SEL-1, and Inconel 713 cracked with from 10 to 12 starts and $6\frac{1}{2}$ to 10 hours at rated speed. Forged Udimet 500 and B and B buckets cracked after 28 starts and 30 hours.

3. Thermal-stress fatigue cracks did not progress rapidly by stress-rupture to cause fracture of buckets. The one bucket that fractured during the test had run with cracks for 31 hours. This bucket fractured by progression due to mechanical fatigue of a crack initiated by stress-fatigue. Other buckets ran with cracks for as long as 63 hours without fracture.

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National Aeronautics and Space Administration
Cleveland, Ohio, July 20, 1959

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TABLE I. - TYPICAL CHEMICAL COMPOSITION OF ALLOYS

| Alloy | Method of fabrication | Weight percent of elements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Ni | Co | Cr | Mo | Ti | Al | C | B | Cb |
| SEL-1 | Vacuum cast | Bal(49) | 27 | 15 | 2.5 | 2.25 | 3.75 | 0.1 | --- | -- |
| B and B | Vacuum cast | Bal(44) | 30 | 15 | 5 | 2.5 | 3 | --- | 0.5 | -- |
| Inconel 713 | Argon cast | Bal(76) | -- | 12 | 4 | .5 | 5.5 | --- | --- | 2 |
| Udimet 500 | Vacuum cast | Bal(55) | 15 | 20 | 4 | 3.0 | 2.75 | .1 | --- | -- |
| Udimet 500 | Wrought | | | | | | | | | |

TABLE II. - NUMBER OF BUCKETS ENGINE-TESTED AND HEAT TREATMENT APPLIED

| Alloy | Number of buckets tested | Heat treatment |
|---|---|---|
| SEL-1 | 21 | Solution-treat, 2050° F, 2 hr; air-cool; age, 1400° F, 16 hr; air-cool |
| B and B | 10 | |
| Inconel 713 | 22 | None (as-cast) |
| Udimet 500 cast | 19 | Solution-treat, 1975° F, 2 hr; air-cool; first age, 1550° F, 16 hr; air-cool; second age, 1400° F, 16 hr; air-cool |
| Udimet 500 wrought | 22 | |
| TOTAL | 94 | |

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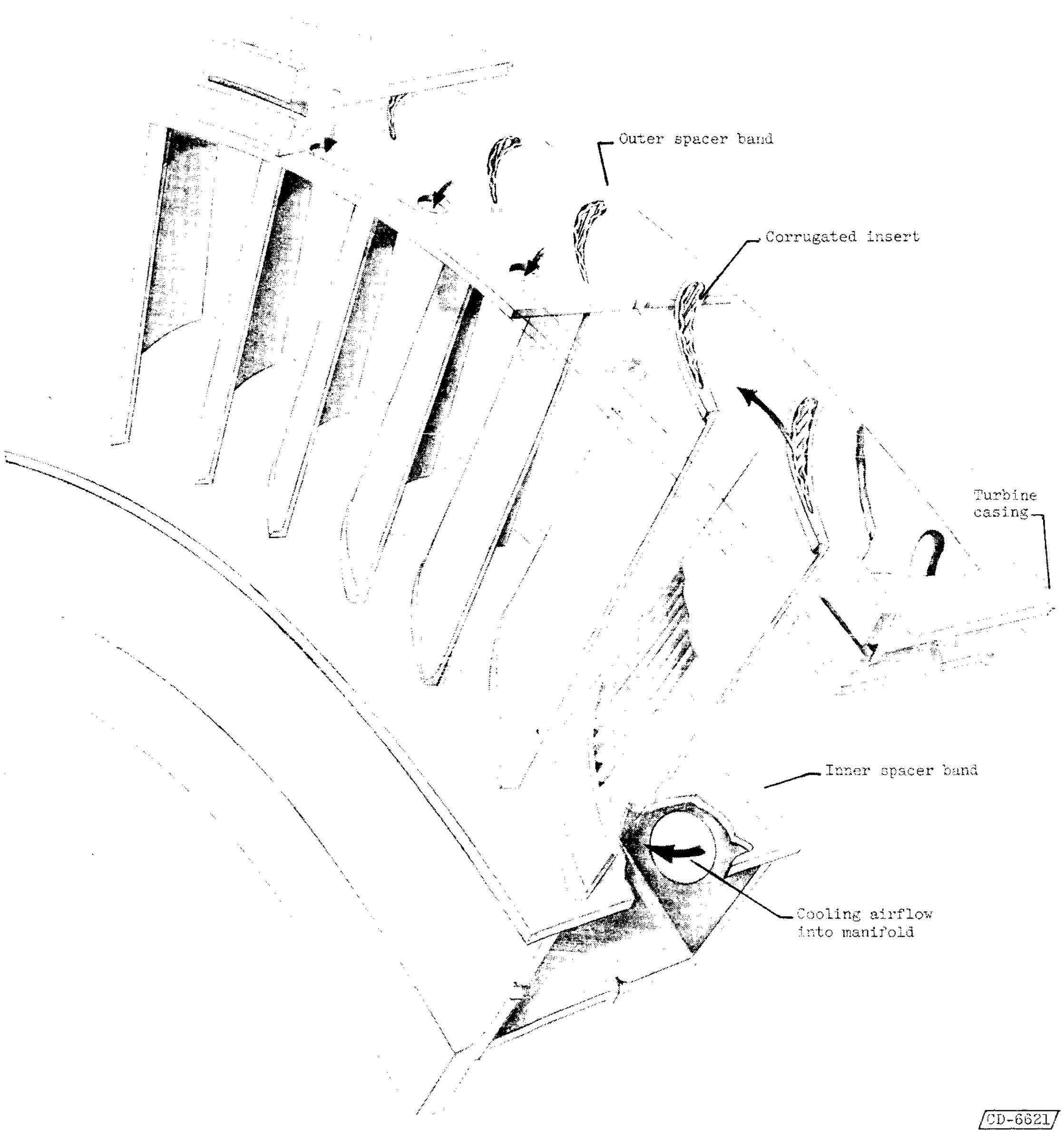


Figure 1. - Method of cooling turbine stator blades.

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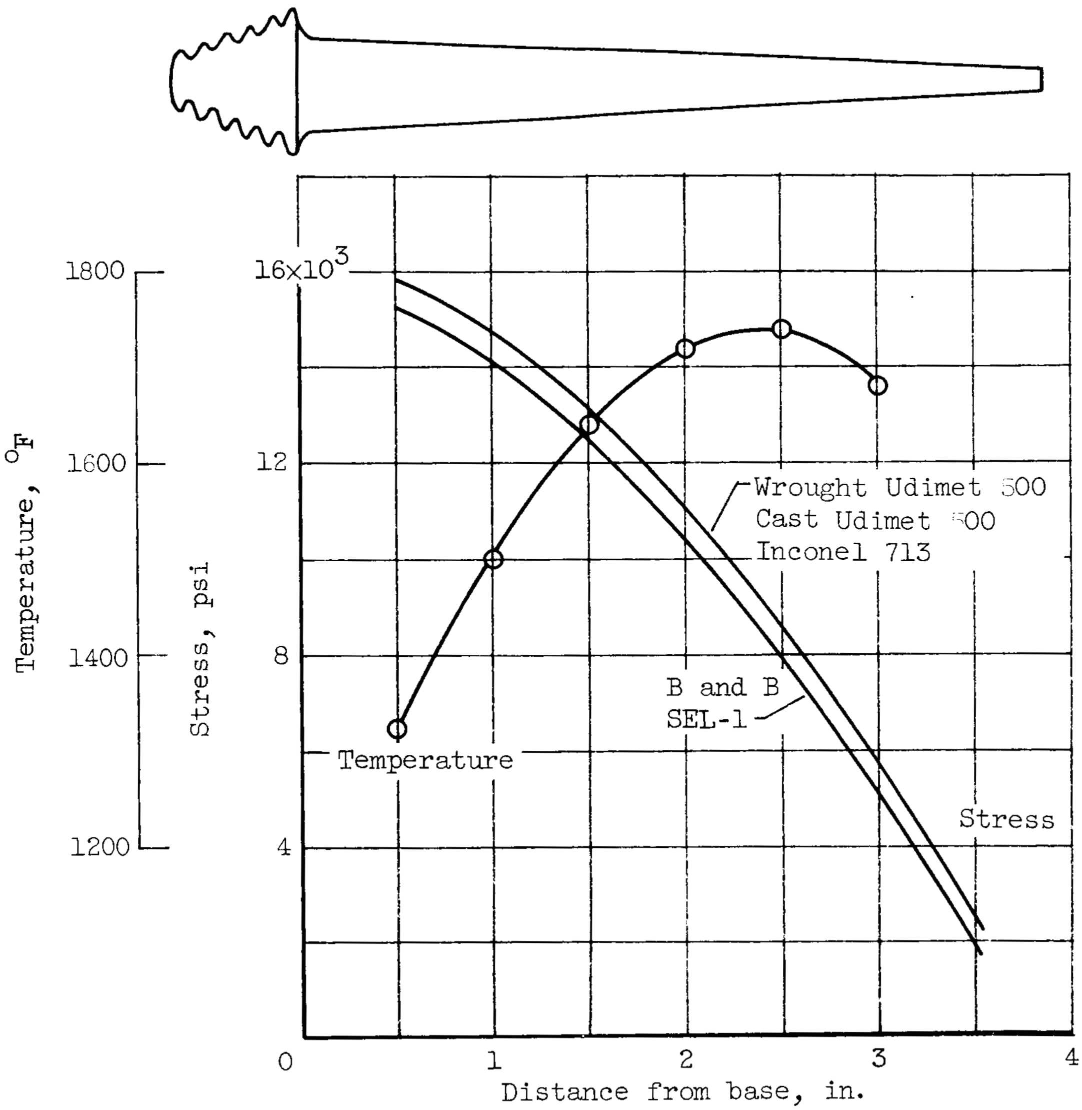


Figure 2. - Bucket stress and temperature distributions at rated conditions.

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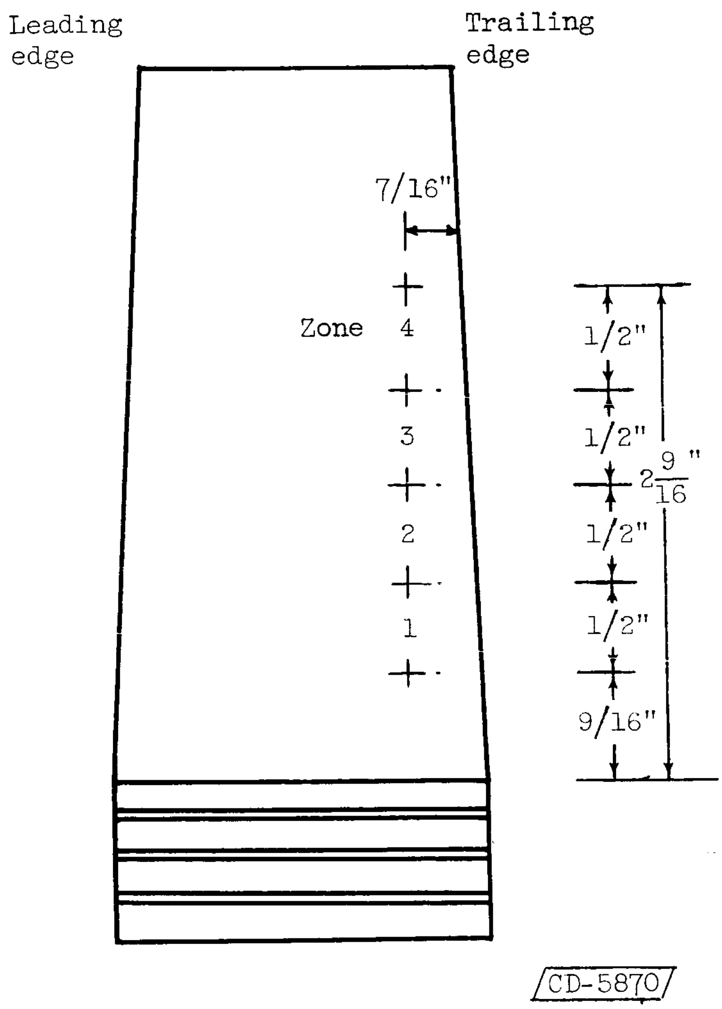


Figure 3. - Scribed bucket for elongation measurements.

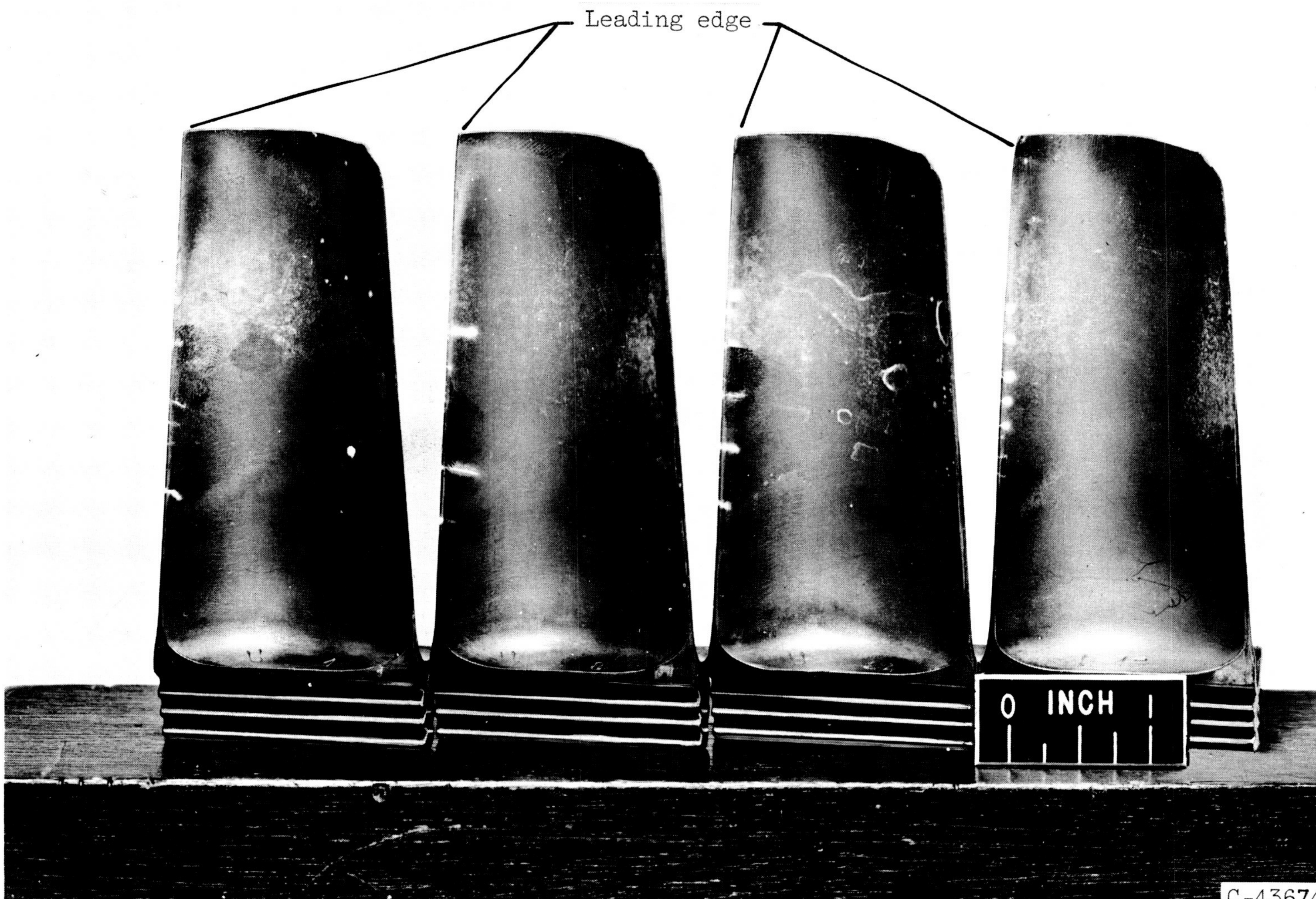


Figure 4. - Typical thermal-fatigue cracked buckets.

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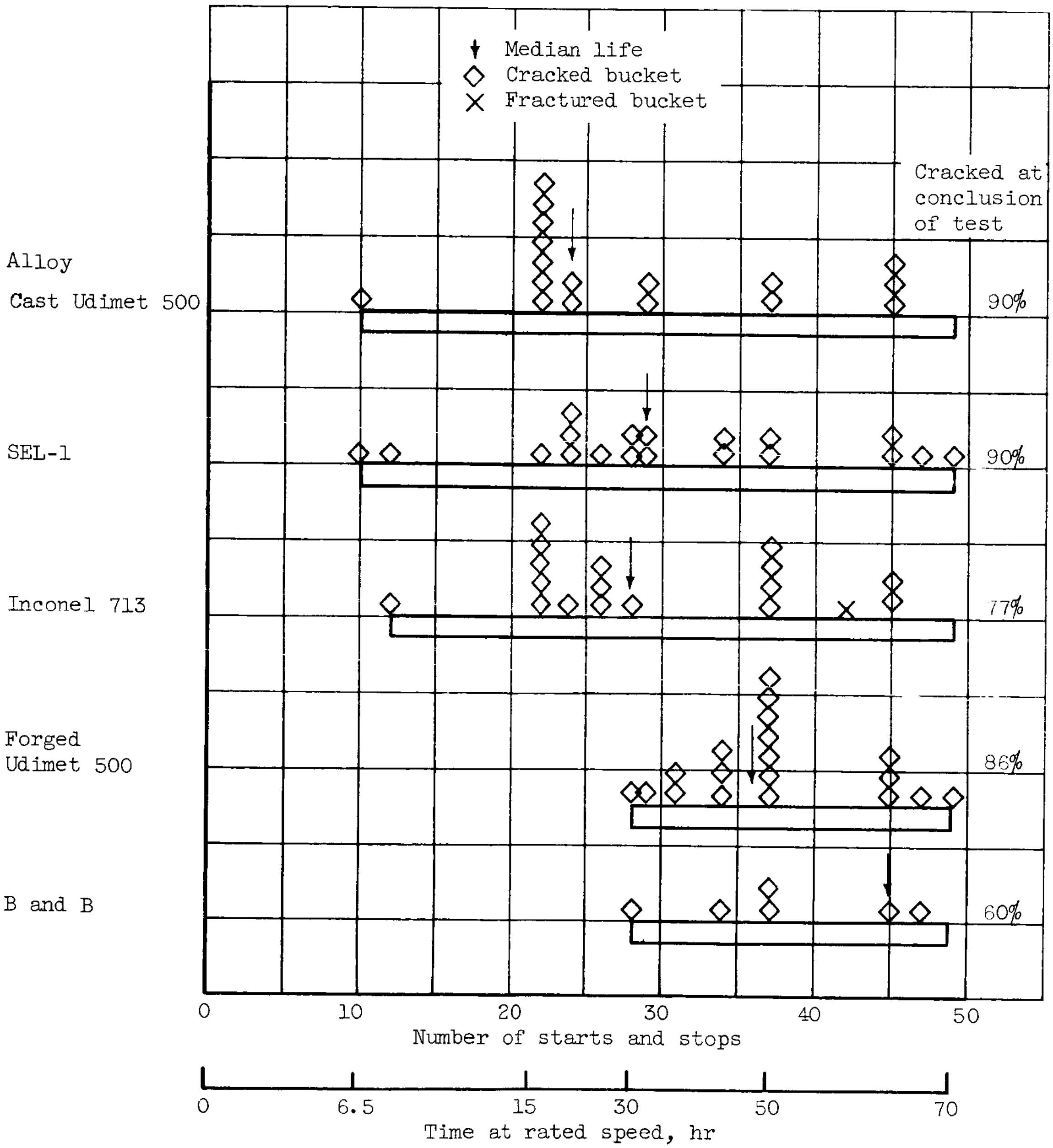


Figure 5. - Engine performance of turbine buckets operated at 1700° F.

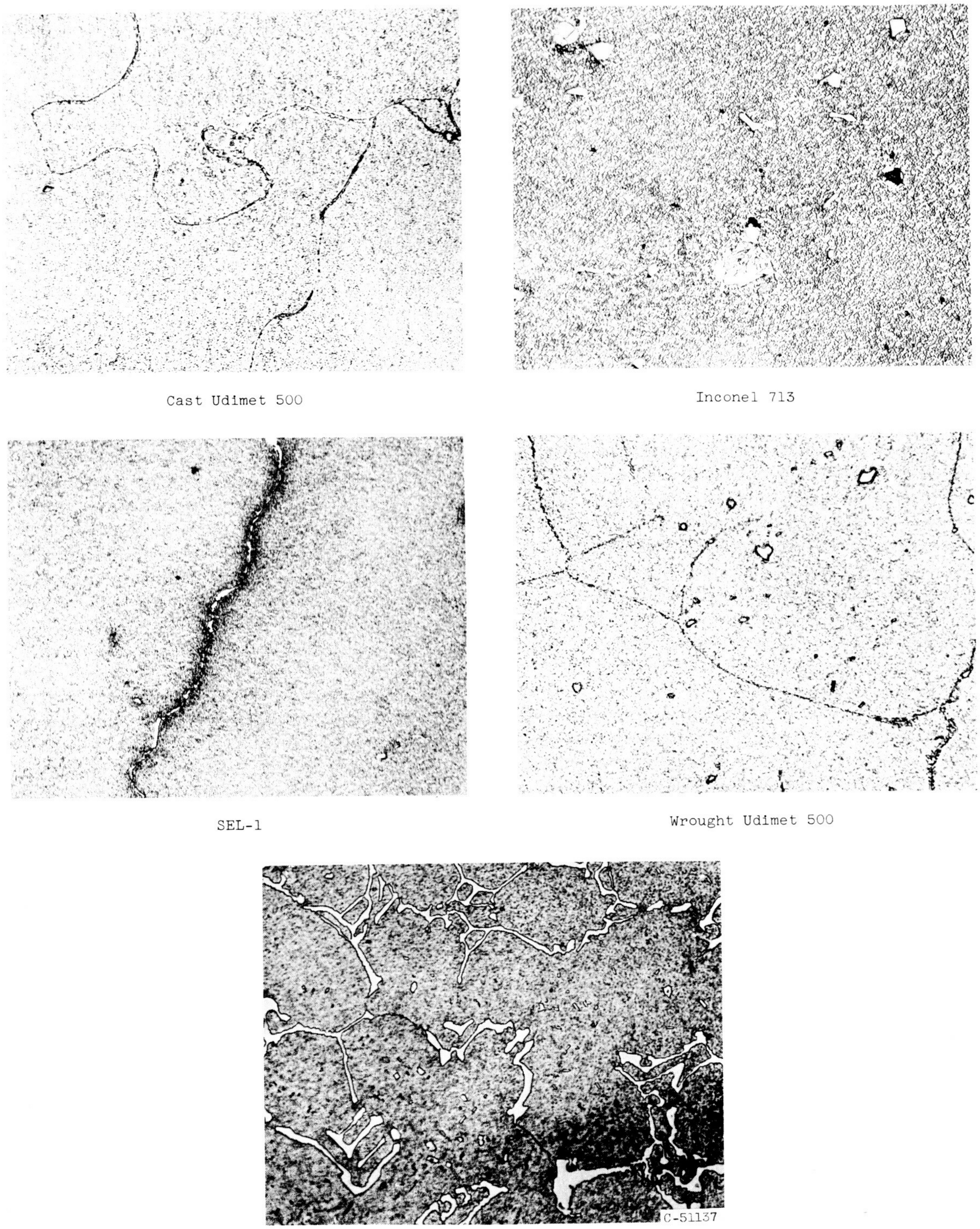


Figure 6. - Typical microstructures of buckets. Etchant: 10 percent HF, 20 percent $HNO_3$. X750.